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**Abstract:** From the early days of remote sensing until today, there has been a wide range of applications of remote sensing data for agricultural management. Improvements in spatial, spectral and temporal resolution of available data products together with precision agriculture have meant an increase in the availability of services and products that help to manage agricultural operation more efficiently and profitably. Imagebased remote sensing offers the potential to provide spatially and temporally distributed information for agricultural management. Remote sensing information can improve the capacity and accuracy of decision support systems (DSS) and agronomic models by providing accurate input information or as a means of within-season calibration or validation. Crop phenology is an important variable required by precision crop management systems (PCMS) in support of time-critical crop management (TCCM). Estimates of crop development, which are used for nutrient deficiencies detection, crop yield prediction or timing of forthcoming harvest are important in agricultural planning and policy making. While the collection of information on the status of biophysical and biochemical characteristics of a crop canopy, that can be correlated to its phenology, is time consuming and limited to punctual measurements, remote sensing allows large and continuous radiometric measurements. Parameters retrievable by a remote sensing system must have an impact on the spectral signal of vegetation canopies. Biophysical parameters are easier to determine because they affect broader spectral regions, whereas biochemical concentrations are more difficult to assess since their spectral features are small and therefore only detectable by hyperspectral sensors. In this paper, a methodology to track the main development stages of two cereals relevant for agricultural purposes and precision farming needs, based on hyperspectral data, is presented. An investigation of the suitability of four key parameters to track a crop stand's vitality and an error assessment are performed. Leaf area index (LAI), fraction of absorbed photosynthetically active radiation (FAPAR), water content and chlorophyll content are defined as the main parameters reflecting vitality and therefore alter with the plants' phenological stage.

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# Spectroradiometry as a Tool for Phenological Characterization of Agricultural Crop Stands

## MATHIAS KNEUBÜHLER<sup>1</sup>

*From the early days of remote sensing until today, there has been a wide range of applications of remote sensing data for agricultural management. Improvements in spatial, spectral and temporal resolution of available data products together with precision agriculture have meant an increase in the availability of services and products that help to manage agricultural operation more efficiently and profitably. Image-based remote sensing offers the potential to provide spatially and temporally distributed information for agricultural management. Remote sensing information can improve the capacity and accuracy of decision support systems (DSS) and agronomic models by providing accurate input information or as a means of within-season calibration or validation. Crop phenology is an important variable required by precision crop management systems (PCMS) in support of time-critical crop management (TCCM). Estimates of crop development, which are used for nutrient deficiencies detection, crop yield prediction or timing of forthcoming harvest are important in agricultural planning and policy making.*

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## 1 Introduction

Between April and August 1999 periodic observations of a spring wheat and a winter barley field have been performed in an intensively cultivated agricultural area, the Limpach Valley (470 m a.s.l.) located in Western Switzerland. In addition, the two fields were covered by the HyMap imaging spectrometer on July 16<sup>th</sup> 1999, one day prior to harvest of the winter barley field. Wheat is the most important cool-temperate cereal in the world, being followed by barley. Wheat cultivars cover more than 30% of Switzerland's acreage for agricultural products, barley is grown on over 15% of this area.

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The selection of biophysical and -chemical variables to be investigated in this study is driven by their ability to track the phenological development of a plant. This implies detectable gradients of the observed data over time. In addition, it must be possible to ascertain them by means of reflectance measurements from a remote sensor. Data collection included spectroradiometric measurements of the crop canopy, determination of leaf area index (LAI), fraction of absorbed photosynthetically active radiation (FAPAR), plant-, leaf- and grain-water content and chlorophyll content. The plant growth stage was characterized using a decimal code (DC) for the growth stages of cereals, developed by Zadoks et al. [25]. According to this code, the phenological development of crops can be divided into a vegetative, a generative and a reproductive phase. The vegetative phase consists of the growth stages seedling growth (DC 10-19) and tillering (DC 20-29), the generative phase of stem elongation (DC 30-39), booting (40-49), inflorescence emergence (DC 50-59), and anthesis (DC 60-69), the reproductive phase of milk development (DC 70-79), dough development (DC 80-89), and ripening (DC 90-99). Data takes were aimed to representatively cover all these phenological stages. Mean dates and durations of phenological stages of cereals were used as a starting point [21][22][15]. Spectroradiometric data was collected using an ASD-Field Spectrometer covering the wavelength range from 0.4  $\mu\text{m}$  to 2.5  $\mu\text{m}$ . Leaf area index is determined using a LICOR LAI-2000 meter [24] and the fraction of absorbed photosynthetically active radiation is determined using a ceptometer [8]. Chlorophyll a and b content was determined from samples in the laboratory using the equations of Lichtenthaler [17]. Plant-, leaf- and grain-water content are measured by oven-drying of the samples.

## 2 Methodology

### 2.1 Measurement Plan

Both, the spectral characterization of an agricultural stand's phenology and the retrieval of quantitative information of plant variables from spectral data describing the stand's vitality status depend on accurate measurements. A standardized measurement plan, incorporating spectral data takes and acquisition of plant vitality parameters was developed. Sampling strategy considerations are based on temporal and spatial requirements as well as sample size considerations. Field and laboratory measurements consist of:

*Spectroradiometric measurements of the vegetation canopy using an ASD-Field Spectrometer.* To satisfactorily characterize the spectral variability within the crop fields, 50 to 60 reflectance measurements were recorded, performing stratified random sampling across a transect along the diagonal of one half part of the fields under investigation. Each measurement taken was visually described as being of dense, medium or low vegetation cover.

*Determination of leaf area index using a LICOR LAI-2000 Meter.* Acquisition of about 20 LAI measurements was performed in the same manner as for the spectroradiometric measurements. Since LAI data strongly depends on the canopy architecture, which itself varies during the day, the measurements were carried out around solar noon, weather permitting.

*Determination of the fraction of absorbed photosynthetically active radiation (FAPAR) by the canopy.* FAPAR measurements were carried out using a ceptometer based on the following equation [13]:

$$FAPAR = 1 - \frac{PAR_r + (PAR_t - PAR_s)}{PAR_0},$$

where  $PAR_t$  upward radiation at the top of the canopy,  $PAR_b$  downward radiation at the bottom of the canopy,  $PAR_s$  radiation reflected at soil surface and  $PAR_0$  incoming radiation at the top of the canopy.

To measure FAPAR in the field, the abovementioned radiation fluxes must be measured independently. Approximately 20 FAPAR values were recorded for each of the two agricultural stands per measurement day. The data was acquired randomly along a transect, and characterized as being of dense, medium or sparse vegetation coverage.

*Determination of plant-, leaf- and grain-water content.* Plant-, leaf- and grain-samples of a mean vegetation stand were collected and placed in a drying oven at 85° C for 48 hours (weight constancy). The weight and leaf area of the fresh samples were measured before drying to determine water content from weight loss.

*Determination of leaf chlorophyll content.* Leaf samples were collected in the field and taken to the laboratory for chlorophyll extraction. The photometric determination of chlorophyll a and b was performed with a CADAS-100 spectralphotometer [16] in 100% acetone using the equations of Lichtenthaler [17]:

$$\begin{aligned} C_a &= 11.24 \cdot A_{661.6} - 2.04 \cdot A_{644.8}, \\ C_b &= 20.13 \cdot A_{644.8} - 4.19 \cdot A_{661.6}, \\ C_{a+b} &= 7.05 \cdot A_{661.6} + 18.09 \cdot A_{644.8}, \end{aligned}$$

where A is the measured absorbance value. The leaf area of each leaf is determined using a LICOR LI-3100 Leaf Area Meter [18].

*Characterization of the growth stage of each measurement day using a decimal code for growth stages of cereals according to Zadoks et al. [25].*

## 2.2 Data Analysis

Each of the four biophysical and biochemical parameters chosen to track the vitality status of a crop stand (LAI, FAPAR, water content, chlorophyll content) is related to the spectral data of the corresponding phenological stages, following the methods described below.

### 2.2.1 Estimating LAI

LAI estimation is based on a semi-empirical reflectance model that calculates LAI of a green canopy based on the WDV (weighted difference vegetation index) and the inverse of an exponential function [5][6]. The WDV is a weighted difference between the measured reflectances  $\rho(\lambda_{NIR})$  and  $\rho(\lambda_{RED})$ , assuming that the ratio of these two reflectances is constant for a certain type of bare soil. In this way, the influence of soil background is corrected:

$$WDV = \rho(\lambda_{NIR}) - C \cdot \rho(\lambda_{RED}),$$

where  $C = \frac{\rho_{SOIL}(\lambda_{NIR})}{\rho_{SOIL}(\lambda_{RED})}$ .

The LAI is calculated as:

$$LAI = \frac{-1}{\alpha} \cdot \ln \left[ 1 - \frac{WDV}{\rho_{\infty}(\lambda_{NIR})} \right],$$

where  $\alpha$  describes the rate at which the abovementioned function runs to its asymptotic value and  $\rho_{\infty}(\lambda_{NIR})$  is the asymptotic limiting value for the WDV. Parameters  $\alpha$  and  $\rho_{\infty}(\lambda_{NIR})$  must be estimated empirically from a training set.

### 2.2.2 Estimating FAPAR

The fraction of photosynthetically active radiation is often expressed as an exponential function of LAI [1]:

$$FAPAR = A \cdot [1 - B \cdot \exp(-C \cdot LAI)],$$

where  $A$ ,  $B$  and  $C$  must be estimated empirically from a training set.

### 2.2.3 Estimating Water Content

Although the spectral reflectance properties of vegetation canopies are determined primarily by the absorption and scattering processes within the plant material and the stand's structure, there are superimposed effects of absorption by water and other biochemical constituents. Early studies by Gates et al. [10], Sinclair et al. [23] and Gausman [11] showed that in the near- and shortwave-infrared region, a negative relationship between leaf water content and leaf reflectance can be found. Water content determination of a whole plant canopy is highly influenced by canopy characteristics, making reflectance a mixture of contributions from plant biochemicals, canopy structure and soil background contribution. Since water content and green biomass are positively correlated, observed high positive correlations between canopy water content and reflectance values in this region [20] are basically caused by biomass and not by water itself. Nevertheless, this relation bears the potential for canopy water estimation from a remote sensor in the near-infrared region. In this study, determination of plant water content is performed using stepwise multiple linear regression from wavelengths showing highest correlation of measured water content and corresponding spectral data for all phenological stages available. Plant water content  $c$  can be expressed as:

$$c = a_0 + \sum_{i=1}^n a_i \cdot \rho(\lambda_i),$$

where  $c$  is the plant water content,  $n$  the number of wavelengths  $\lambda_i$  used in the regression model,  $a_0$  the regression constant,  $a_{i=1,n}$  the coefficients of the selected regressor wavelengths  $\lambda_i$ , and  $\rho(\lambda_i)$  the reflectances of the selected regressor wavelengths  $\lambda_i$  between 400-1800 nm.

### 2.2.4 Estimating Chlorophyll Content

Most non-destructive techniques for the determination of chlorophyll relate the leaf reflectance at about 675 nm to the concentration of the total chlorophyll. Chappelle [4] used ratio spectra that allow the identification of reflectance bands corresponding to the absorption bands of specific pigments. The developed *ratio analysis of reflectance spectra* (RARS) *algorithm* allows estimation of the concentrations of chlorophyll a and b per unit mass solvent using a linear relationship. Blackburn [2] describes the relationship of  $RARS_a$  with canopy chlorophyll a concentration per unit area using an exponential function.  $RARS_b$  is reported to have no relationship with chlorophyll b.

The algorithms for chlorophyll a and b are defined as follows:

$$RARS_a = \frac{\rho_{675}}{\rho_{700}} \text{ and } RARS_b = \frac{\rho_{675}}{\rho_{650}} \cdot \rho_{700},$$

where  $r_i$  is the reflectance at the wavelength  $i$ .

Blackburn developed the *pigment specific simple ratio* (PSSR) *algorithm*. An exponential function is reported to best describe the relationship of PSSR and chlorophyll a and b concentration.  $PSSR_a$  and  $PSSR_b$  are defined as follows [2]:

$$PSSR_a = \frac{\rho_{800}}{\rho_{680}} \text{ and } PSSR_b = \frac{\rho_{800}}{\rho_{635}}.$$

In addition, the absolute feature height and feature width of the 675 nm chlorophyll a absorption region are investigated for the spectral data of the different phenological stages, in order to compare the results to measured chlorophyll concentrations.

## 3 Results and Conclusions

### 3.1 LAI

Although the concept of estimating LAI from WDVl was developed for green vegetation [5][6], it is reported to be likewise applicable to the phenological stages of flowering and ripening [7], when LAI and photosynthetic activity decrease. In this study, the growth stages of the vegetative phase and the generative phase until the beginning of anthesis (flowering) are subsequently referred to as *growing phase*, the stages of anthesis and the following reproductive phase are referred to as *senescing phase*.

Best results for LAI estimation from WDVl were found for separate treatment of the *growing* and the *senescing phase*. The combined use of the two data sets of spring wheat and winter barley for LAI estimation yielded the best results:

The *growing phase* (solid lines in Figure 1) of both wheat and barley is best described by a joint dataset of both cultivars over the whole cropping cycle. Fit-parameters for LAI estimation from WDVl of both spring wheat and winter barley can be used interchangeably.

The *senescing phase* (dashed lines in Figure 1) of both wheat and barley is best described by a joint data set of both cultivars over the *senescing phase*. Especially LAI estimates in the senescing phase are more accurate under absence of data from the *growing phase*.

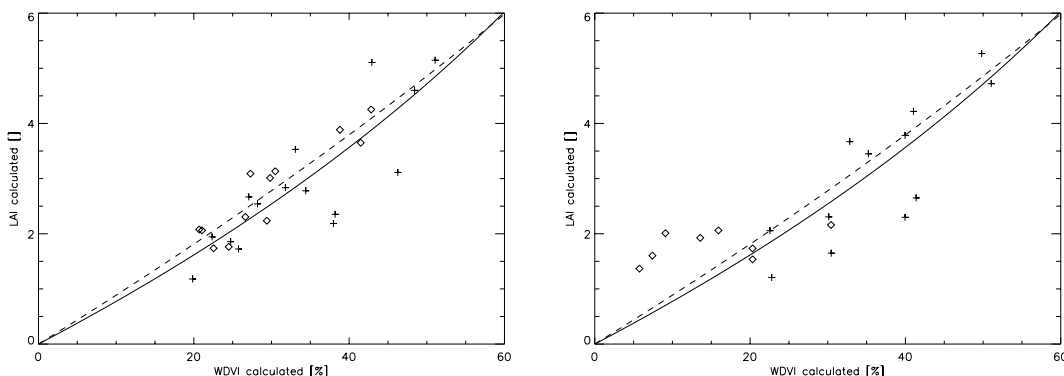


Figure 1: Fitted relationship between WDVl and LAI for spring wheat (left, rms\_rel *growing*: 20.2%, rms\_rel *senescing*: 13.1%) and winter barley (right, rms\_rel *growing*: 23.0%, rms\_rel *senescing*: 100.7%). The solid line represents the exponential fit for the *growing phase*, the dashed line for the *senescing phase*. Crosses denote WDVl values and corresponding measured LAI of the *growing phase*, asterisks WDVl values and measured LAI of the *senescing phase*. The presence of weeds and standing litter material strongly deteriorates LAI estimation from WDVl towards the end of the cropping cycle.

LAI estimates of winter barley in the *senescing phase* suffer from heavy weed infestation during ripening. This disturbs both the LAI-2000 meter readings and the spectroradiometric measurements (WDVl values). In addition, the LAI-2000 meter's measurement design, which is based on a radiation interception method involving all elements of a vegetation canopy's architecture, such as green leaves, litter and ears, tends to overestimate LAI of a crop stand mainly towards the end of a vegetation period [24]. As a consequence, it can be concluded, that LAI estimates based on the joint data set of *senescing* spring wheat and winter barley yields more accurate results of LAI of winter barley towards the end of the cropping cycle than can actually be indicated by the applied accuracy investigation of Figure 1. Almost

any weeds were present in the winter barley field anymore at the day of the HyMap data take. As can be seen in Figure 6 (right), the mean LAI value calculated on the basis of the imaging spectrometer data is LAI=0.32 for the barley field, which is much lower than the values recorded under weed presence. An LAI of 0.41 was recorded using the LAI-2000 meter one day after the overflight (see Table 1).

### 3.2 FAPAR

A plant's capacity to absorb incoming radiation for biomass production is dependent on its physiological state and therefore related to its phenological stage. Highest LAI values for spring wheat were measured during stem elongation for DC 32-33 (2<sup>nd</sup> to 3<sup>rd</sup> node detectable). Highest FAPAR values were recorded on the same day. LAI and FAPAR values stay constantly high until completion of anthesis.

Winter barley showed highest measured LAI and FAPAR values during inflorescence emergence (DC 55-59). Contrary to spring wheat, the ears of winter barley are larger and tend to bend sideward, preventing incoming radiation from penetrating the canopy, which leads to highest observed LAI and FAPAR readings.

Estimation of FAPAR can be performed using an exponential relationship with LAI. The fitted relationship between modelled LAI values derived from WDVl (see chapter 3.1) and measured FAPAR for spring wheat, winter barley and a joint data set are presented in Figure 2 (left). Based on the derived fit parameters, FAPAR can be modelled over the cropping cycle (Figure 2, right).

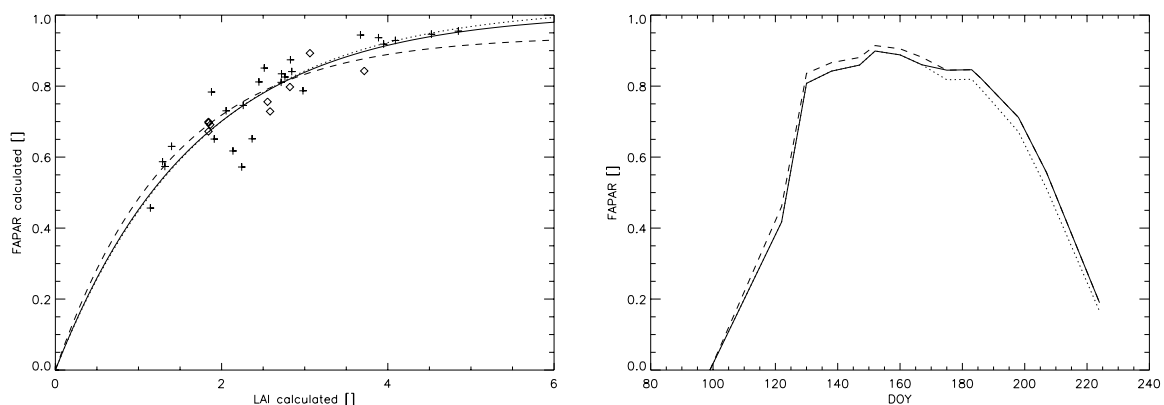


Figure 2: Left: Fitted relationship between LAI values derived from WDVl and measured FAPAR values for spring wheat (dotted line), winter barley (dashed line) and a joint data set (solid line). Crosses denote LAI values and corresponding, measured FAPAR values of spring wheat, asterisks LAI values and corresponding, measured FAPAR values of winter barley (rms\_rel spring wheat: 8.2%, rms\_rel winter barley: 4.1%, rms\_rel joint data set: 7.5%). Right: Modelled FAPAR of spring wheat over the cropping cycle (solid line: FAPAR from optimal fit parameters for separate treatment of *growing* and *senescing phase*; dashed line: FAPAR from LAI based on fit parameters of *senescing phase*; dotted line: FAPAR from LAI based on fit parameters of *growing phase*. DC 32-33 of the phenological cycle show maximum values for both LAI and FAPAR of spring wheat.

### 3.3 Water Content

Water content determination in the laboratory was performed for plant-, leaf- and grain-samples. As a general trend, water content decreases from the early stages of plant growth towards the end of the cropping cycle. Whereas plant- and grain-water content decrease steadily towards the end of the *senescing phase*, leaf-water content decreases abruptly from the water ripe stage (DC 71), clearly marking the beginning of the reproductive phase.

Since spectroradiometric measurements of a crop canopy, as recorded by a remote sensor, do not represent single leaves, but a whole plant, the extraction of plant-water content from spectroradiometric data was investigated. Determination of predictive wavelengths  $\lambda_i$ , the regression constant  $a_0$  and regression coefficients  $a_i$  was carried out on a calibration data set of measured plant-water content and corresponding spectral data for all phenological stages available. The investigation was performed at HyMap resolution to test the suitability of an imaging spectrometer's spectral resolution. First derivative analysis of the wavelength dependent correlation coefficient  $r$  was applied to select predictive spectral wavebands, that are consecutively entered into stepwise multiple linear regression. The optimal number of regressor wavelengths  $\lambda_i$  was determined by a maximal multiple coefficient of determination  $R^2$  and a minimal *relative rms* of a verification data set (Figure 3).

The phenological stages of the reproductive phase (milk development (DC 70-79), dough development (DC 80-89) and ripening (DC 90-99)) show characteristic water contents of the grains [25]. Strong linear correlations ( $r=0.99$ ) of plant-water content and grain-water content were found for the time between DC 71 (caryopsis water ripe) and DC 92 (caryopsis hard) under dry atmospheric conditions. Nevertheless, humid conditions around the stage of hard dough (DC 87) can prevent the grains from losing moisture and reaching the desired grain moisture content of 15% at harvest (DC 92). This effect disturbs the linear relationship between plant- and grain-water content.

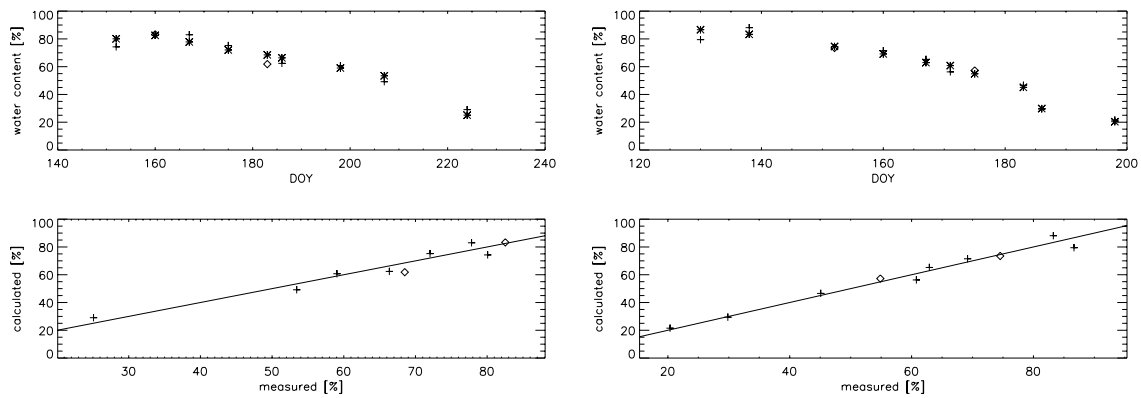


Figure 3: Determination of plant water content of spring wheat (left, rms\_rel of the verification data: 7.7%) and winter barley (right, rms\_rel of the verification data: 3.1%) using stepwise multiple linear regression. Asterisks denote plant water content as measured in the laboratory, crosses are water content values from the calibration set of the multiple regression and squares are water content values calculated for validation of the regression equation.

### 3.4 Chlorophyll Content

Several studies have demonstrated that determination of leaf chlorophyll content from spectroradiometric data is possible [14][4][12][2], whereas chlorophyll determination of spectral data from vegetation canopies suffer from influences of the total biomass (LAI) [9]. The applied algorithms in Figure 4 were originally developed for soybean leaves (RARS) and senescent tree leaves (PSSR) and applied to a canopy of bracken throughout a growing season [3]. None of the methods was applied to agricultural crop stand canopies.

Figure 4 shows a strong variation over time in the reflectance ratios of RARS and PSSR and chlorophyll a and b content per unit area. Both algorithms show a turning point, which, for spring wheat is reached at the stages of *flag leaf sheath opening* / *half of inflorescence emerged* (DC 47, 55). For winter barley, this turning point is only reached at *the beginning of anthesis* (DC 61). Nevertheless, the strong relationships between the reflectance ratios and chlorophyll concentrations using an exponential function, as described in the literature, could



not be found for the two data sets under investigation. It is obvious that the two algorithms are not able to track chlorophyll of plants that undergo such fundamental physiological changes over a cropping cycle as crop stands do, by an exponential function.

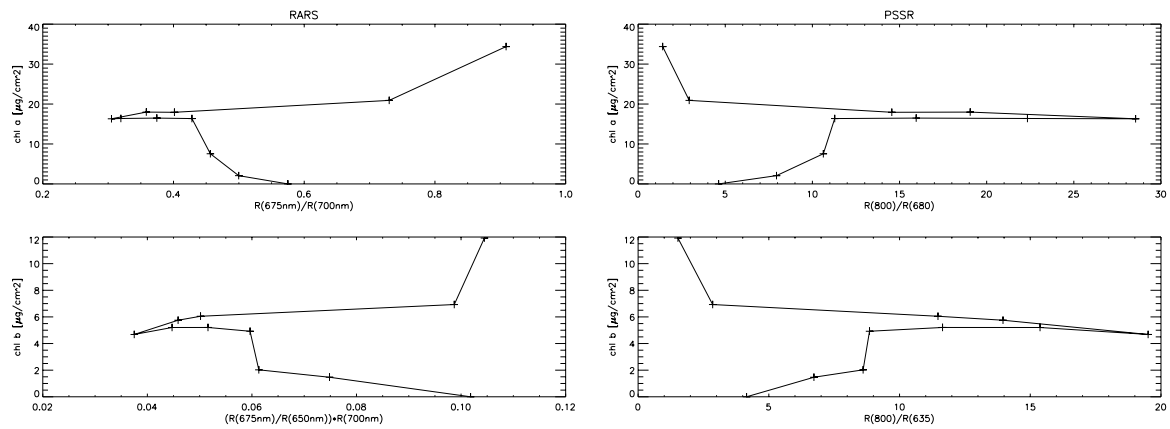


Figure 4: Ratio analysis of reflectance spectra (RARS) algorithm (left) and pigment specific simple ratio (PSSR) algorithm (right) for a dense spring wheat canopy during a cropping cycle. Both algorithms show a strong variation in the relationship between reflectance ratio and chlorophyll a and b content per unit area.

Calculation of the absolute feature height (Figure 5, left) and feature width of the 675 nm chlorophyll a absorption region of spring wheat show high correlations with LAI derived from WDVl (Figure 5, middle), whereas measured chlorophyll a and b concentrations per leaf area decrease during the vegetation period (Figure 5, right). As a consequence, it must be concluded, that the spectral response of a vegetation canopy as seen by a remote sensor around the main chlorophyll a absorption region (675 nm) is predominantly driven by green biomass (green LAI), not chlorophyll per leaf area. This makes chlorophyll estimation of a crop stand over a vegetation period impossible, using the abovementioned spectral region.

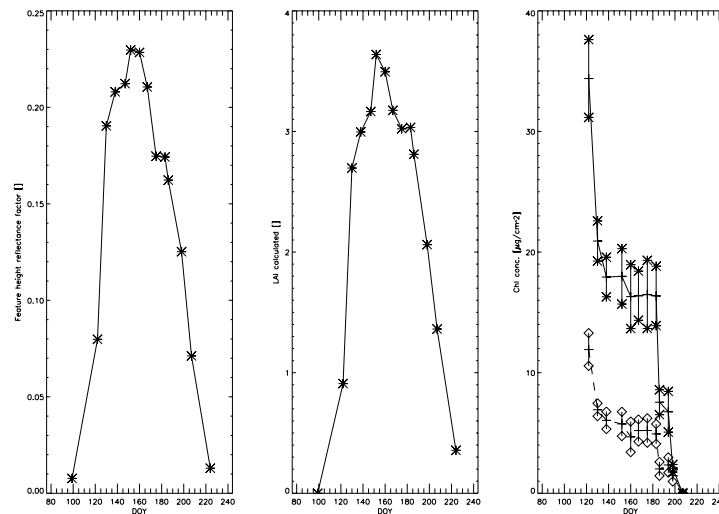


Figure 5: Absolute feature height of the 675 nm chlorophyll a absorption feature (left), calculated LAI from WDVl (middle) and chlorophyll a,b concentration including one standard deviation from mean for spring wheat over a cropping cycle (right, solid line: chl a, dashed line: chl b).

### 3.5 Application to HyMap Imaging Spectrometer Data

The algorithms used for retrieval of LAI, FAPAR and plant water content, as described in Chapter 2.2, were applied to an imaging spectrometer data set of HyMap using the derived parameters from the extensive ground truth data set. The two fields of spring wheat and winter barley were flown by HyMap on July 16<sup>th</sup>, one day prior to harvest of winter barley (DC 94, over-ripe) and covering the medium milk stage (DC 75) of spring wheat. The data was atmospherically corrected to get apparent reflectances, using ATCOR4 [19]. Figure 6 shows the spatial distribution of LAI, FAPAR and plant water content of spring wheat (left) and winter barley (right) during the overflight.

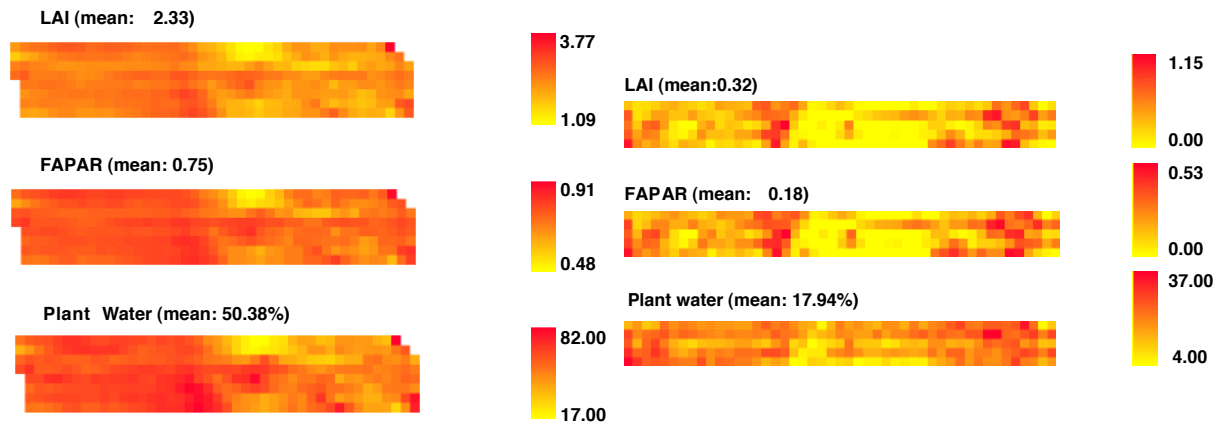


Figure 6: Determination of LAI, FAPAR and plant-water content from HyMap data for the spring wheat field (left) and the winter barley field (right), using the applied methods and derived parameters of the ground truth data acquired during the 1999 cropping cycle

Table 1 holds mean values of the retrieved vegetation parameters of the observed spring wheat and winter barley field as measured (July 17<sup>th</sup> 1999) and derived from HyMap data (July 16<sup>th</sup> 1999).

Table 1: Retrieved and measured values of LAI, FAPAR and plant water content of the observed spring wheat and winter barley field for the time of the HyMap overflight. (The field measurements were performed one day after the overflight.)

retrieved parameter	spring wheat HyMap July 16 <sup>th</sup> 1999	spring wheat measured July 17 <sup>th</sup> 1999	winter barley HyMap July 16 <sup>th</sup> 1999	winter barley measured July 17 <sup>th</sup> 1999
mean LAI []	2.33	2.13	0.32	0.41
mean FAPAR []	0.75	0.78	0.18	-
mean plant water [%]	50.38	59.04	17.94	20.36

As far as the suitability of the four observed parameters (LAI, FAPAR, water content and chlorophyll content) is concerned to track the phenological stages of winter barley and spring wheat, it can be concluded, that the estimation of LAI, FAPAR and plant water content from hyperspectral measurements is possible within the specified accuracies, whereas chlorophyll estimation was not successful due to canopy structural effects (LAI) present in the observed spectral region. The comprehensive collection of ground truth data during the 1999 field campaign bears the potential to relate retrieved LAI, FAPAR and water content values of spring wheat and winter barley from future hyperspectral data takes to specific, corresponding phenological stages.

## 4 References

- [1] Baret, F., Guyot, G.: "Potentials and Limits of Vegetation Indices for LAI and APAR Assessment", RSE, 35: 161-173, 1991
- [2] Blackburn, G. A.: "Spectral Indices for Estimating Photosynthetic Pigment Concentrations: A Test Using Senescent Tree Leaves", Int. J. Remote Sens, 19 (4), pp: 657-675
- [3] Blackburn, G.A.: "Quantifying Chlorophylls and Carotenoids at Leaf and Canopy Scales: An Evaluation of some Hyperspectral Approaches", RSE, 66: 273:285, 1998
- [4] Chappelle, E. W., Moon, S. K., McMurtrey, J. E.: "Ratio Analysis of Reflectance Spectra (RARS): an Algorithm for the Remote Estimation of the Concentrations of Chlorophyll a, Chlorophyll b and Carotenoids in Soybean Leaves", RSE, 39: 239-247, 1992
- [5] Clevers, J. G. P. W.: "The Derivation of a Simplified Reflectance Model for the Estimation of Leaf Area Index", RSE, 25: 53-69, 1988
- [6] Clevers, J. G. P. W.: "The Application of a Weighted Infrared-Red Vegetation Index for Estimating Leaf Area Index by Correcting for Soil Moisture", RSE, 29: 25-37, 1989
- [7] Clevers, J. G. P. W.: "Application of the WDVl in estimating LAI at the Generative Stage of Barley", ISPRS J. Photogramm. Remote Sensing, 46: 37-47, 1991
- [8] Delta-T Device LTD: "Sunfleck Ceptometer User Manual", Decagon Devices Inc., Cambridge England, pp: 28, 1989
- [9] Filella, I., Peñuelas, J.: "The Red Edge Position and Shape as Indicators of Plants Chlorophyll Content, Biomass and Hydric Status", Int. J. Remote Sens., 15 (7), pp: 1459-1470, 1994
- [10] Gates, D. M., Keegan, H. J., Schleter, J. C., and Weidner, V. R.: "Spectral Properties of Plants", App. Optics, Vol. 4, No. 1, pp: 11-20, 1965
- [11] Gausman, H. W.: "Plant Leaf Optical Properties in Visible and Near-Infrared Light", Graduate Studies No. 29, Texas Technical University, Lubbock, Texas, 1985
- [12] Gitelson, A. A., Merzlyak, M., N.: "Remote Estimation of Chlorophyll Content in Higher Plant Leaves", Int. J. Remote Sens., 18 (12), pp: 2691-2697, 1997
- [13] Goward, S. N., Huemmerich, K. F.: "Vegetation canopy PAR absorbance and the normalized difference vegetation index: an assessment using the SAIL model", RSE, 39: 119-140, 1992
- [14] Horler, D. N. H., Dockray, M., and Barber, J.: "The Red Edge of Plant Leaf Reflectance", Int. J. Remote Sens., 4 (2), pp: 273-288, 1983
- [15] Kolbe, W.: "Studies on the Course of Development of Cereals (1968-1984) in Relation to Sowing Time", Pflanzenschutz-Nachrichten Bayer, 37, pp: 337-423, 1984
- [16] Lange, B., GMBH: "Spektralphotometer CADAS 100, Bedienungsanleitung", Lange GMBH Berlin, pp: 59, 1990
- [17] Lichtenthaler, H. K.: "Chlorophylls and Carotenoids: Pigments of Photosynthetic Biomembranes", Methods in Enzymology, 48: 350:382, 1987
- [18] Licor Inc., "LI-3100 AreaMeter",  
<<http://env.licor.com/products/li3100/3100spec.htm>>, 2001
- [19] Richter, R.: "Atmospheric / Topographic Correction for Wide FOV Airborne Imagery: Model ATCOR4", DLR - German Aerospace Center, DLR-IB 552-05/00, Version 2.0, 2000
- [20] Rollin, E. M., Milton, E. J.: "Processing of High Spectral Resolution Reflectance Data for the Retrieval of Canopy Water Content Information", RSE, 65: 86-92, 1998
- [21] Russell, G.: "Barley Knowledge Base", Commission of the European Communities, Luxembourg, EUR 13040 EN, pp: 135, 1990
- [22] Russell, G., and Wilson, G. W.: "An Agro-Pedo-Climatological Knowledge-Base of Wheat in Europe", Commission of the European Communities, Luxembourg, EUR 15789 EN, pp: 160, 1994
- [23] Sinclair, T. R., Hoffer, R. M., and Schreiber, M. M.: "Reflectance and Internal Structure of Leaves from Several Crops During a Growing Season", Agronomy Journal, 63, pp: 864-867, 1971
- [24] Welles, J. M., and Norman, J. M.: "Instrument for Indirect Measurement of Canopy Architecture", Agronomy Journal, 83, No. 5: 818-825, 1991
- [25] Zadoks, J. C., Chang, T. T., Konzak, C. F.: "A Decimal Code for the Growth Stages of Cereals", Weed Research, 14: 415-421, 1974